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Shergotty, Zagami, EETA 79001 and QUE 94201

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**STUDIES OF MAGMATIC INCLUSIONS IN THE BASALTIC MARTIAN METEORITES
SHERGOTTY, ZAGAMI, EETA 79001 AND QUE 94201**

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ABSTRACT

Currently there are 12 meteorites thought by planetary scientists to be martian samples, delivered to the Earth after violent impacts on that planet's surface. Of these 12 specimens, 4 are basaltic: Shergotty, Zagami, EETA 79001 and QUE 94201. Basalts are particularly important rocks to planetary geologists- they are the most common rocks found on the surfaces of the terrestrial planets, representing volcanic activity of their parent worlds. In addition, because they are generated by partial melting of the mantle and/or lower crust, they can serve as guideposts to the composition and internal processes of a planet. Consequently these four meteorites can serve as "ground-truth" representatives of the predominant volcanic surface rocks of Mars, and offer researchers a glimpse of the magmatic history of that planet.

Unfortunately, unraveling the parentage of a basaltic rock is not always straightforward. While many basalts are simple, unaltered partial melts of the mantle, others have undergone secondary processes which change the original parental chemistry, such as assimilation of other crustal rocks, mixing with other magmas, accumulation, re-equilibration between mineral species after crystallization, loss of late-stage magmatic fluids and alteration by metamorphic or metasomatic processes. Fortunately, magmatic inclusions can trap the evolving magmatic liquid, isolating it from many of these secondary processes and offering a direct look at the magma during different stages of development. These inclusions form when major or minor phases grow skeletally, surrounding small amounts of the parental magma within pockets in the growing crystal. The inclusion as a whole (usually consisting of glass with enclosed crystals) continues to represent the composition of the parental magma at the time the melt pocket closed, even when the rock as a whole evolves under changing conditions. The four basaltic martian meteorites contain several distinct generations of melt inclusions; those found within early-forming pigeonite, intermediate and late-forming Ti,Fe-oxides and sulfides, and intermediate to late-forming phosphates.

In this summer's study we have made a detailed study of all of the various forms of inclusions found within the 4 basaltic martian meteorites listed above. Glasses and minerals within the inclusions were analyzed using the Cameca SX-100 Electron Microprobe in Building 31. The mineralogy and textural context of the inclusions will then be used to explore the crystallization history of these specimens, and to investigate any differences in crystallization history or parental magma compositions between these rocks. In this manner, the magmatic inclusions provide a road map backwards toward the "parental" compositions for the basaltic martian meteorites and provides significant insight into the igneous processes found within the crust of Mars.

INTRODUCTION

The most common type of surficial igneous rock in the solar system is basalt, and consequently an understanding of basalt mineralogy, chemistry and petrogenesis is crucial for understanding planetary processes. In recent years, particular interest has focused on a group of four basaltic lithologies thought to have come from the planet Mars [see ref. 1 and references therein]. These samples, Shergotty, Zagami, EETA 79001 and QUE 94201, known as the basaltic shergottites, share several common features and in general resemble pyroxene-rich terrestrial basalts. One important feature that these rocks share is the presence of magmatic inclusions in several different minerals within the rock. These magmatic inclusions were formed when ambient melt that was trapped within growing crystals, and as a result they represent the composition of the surrounding magma at various stages in the evolution of the parental magmatic liquid. Previous studies have focused on magmatic inclusions in Shergotty and Zagami pyroxenes to investigate parental magma composition and evolution [2,3]. In this study, we extend this work with studies of inclusions in all four basaltic shergottites (including EETA 79001 and QUE 94201), and also include studies of later generations of melt inclusions found in oxide and phosphate phases.

ANALYTICAL TECHNIQUES

Polished thin sections of Shergotty (UNM 409), Zagami (UNM 993 and UH 233), EETA 79001 (TS 69) and QUE 94201 (TS 6, 37, and 38) were initially examined under a polarizing optical microscope. Backscattered images, elemental maps and quantitative analyses were acquired using the Cameca SX-100 electron microprobe in Building 31 at the Johnson Space Center, at an accelerating potential of 15 keV and a beam current of 20 nA. Beam size varied between 1 and 10 microns depending on the volatile loss of various phases analyzed, and well-characterized standards and ZAF procedures were used to correct for matrix effects.

PETROGRAPHY

The rocks as a whole All of the basaltic shergottites have been previously described by a number of authors: representative papers are listed and only a short description will be provided here [4-7]. These rocks are composed predominantly of relatively Fe-rich pyroxene (pigeonite) and anorthitic feldspar (converted to maskelynite by shock), with varying amounts of secondary minerals such as olivine, augite, Ti- and Fe- oxides, phosphates, and sulfides. Although textures vary from sample to sample, in all four specimens pigeonite generally occurs as elongate, strongly zoned euhedral to subhedral grains, with maskelynite occurring predominantly as an interstitial phase. All four specimens exhibit features consistent with long crystallization histories, such as extremely Fe-rich compositions in the mesostasis, though to varying degrees. Shergotty, as the type lithology of the shergottites, shows the most consistent texture from thin-section to thin-section, with relatively little variation in grain size and the modal percentage of pyroxene, maskelynite and mesostasis from section to section. EETA 79001 also shows little variation in modal abundance of pyroxene and maskelynite, but in hand-sample exhibits a lithological contact between a finer grained, more uniform basaltic lithology (lithology B) and a xenocryst-bearing, less uniform basaltic lithology (lithology A). In this study, only lithology B was examined for inclusions. Zagami resembles Shergotty in modal abundances of pyroxene and maskelynite, but exhibits widely varying grain size from thin section to thin section. In addition, some thin sections of Zagami exhibit significant amounts of "dark, mottled lithology", regions of abundant late-stage Fe-rich mesostasis including fayalite-silica intergrowths and large oxide and phosphate crystals. Like Zagami, QUE 94201 exhibits significant differences in pyroxene and maskelynite habit from thin-section to thin-section. Modal abundances of maskelynite can vary from 30 to 55% and pyroxene can occur as small, concentrically zoned euhedral grains, larger, cryptically zoned

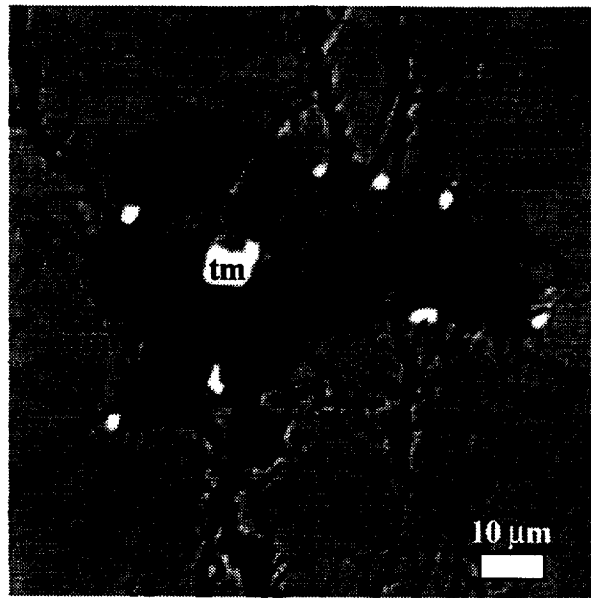


Figure 1. Backscattered electron photomicrograph of typical trapped melt inclusion in Zagami pyroxene (scale bar = 10 μm). The host pyroxene crystal (px1) surrounds several daughter phases including augite (aug), titano-magnetite (tm), chlorapatite needles (ca), and amphibole (amp), as well as glass (gl) representing trapped, uncrystallized magmatic liquid.

Table 1. Representative compositions of host and daughter phases for magmatic inclusions.

<i>Early formed pyroxene host</i>										<i>Early-forming oxide host</i>			
phase	glass	sulfide	whitl.	spinel	augite	pig.	amph.	ilm.	timag.	glass	px-glass	lt glass	dk glass
SO ₃	0.03	93.51	0.07	0.14			0.10			0.06			
P ₂ O ₅	0.39	0.00	53.44	0.00			0.52			0.00			
SiO ₂	72.09	0.16	1.66	0.12	49.70	49.83	34.46			71.31			
TiO ₂	0.17	0.09	0.00	0.17	0.60	0.40	10.34		21.31	51.06	48.85		
Al ₂ O ₃	17.53	0.26	0.39	50.55	1.99	1.21	15.22		2.01	0.05	1.26		
Cr ₂ O ₃	0.04	0.07	0.08	0.84	0.29	0.17	0.10		1.72	0.09	0.44		
MgO	0.09	0.01	2.71	4.92	13.08	16.48	4.50		0.43	0.76	10.87		
CaO	1.66	0.19	44.41	0.12	16.16	5.31	10.45				4.79	0.46	
MnO	0.07	0.04	0.11	0.29	0.51	0.75	0.40		0.45	0.59	0.88	0.04	
FeO	1.14	74.88	2.18	37.63	16.58	24.43	20.94		70.07	46.00	32.94	1.10	
Na ₂ O	3.79	0.00	2.11	0.05	0.23	0.08	1.58				0.04	1.66	
K ₂ O	1.62	0.00	0.07	0.01			0.22					6.98	
total	98.61	170.84	107.22	94.95	99.13	98.66	98.83		96.74	98.78	100.08	96.73	
<i>Late-forming oxide host</i>										<i>Sulfide host</i>			
phase	timag.	ilm.	glass	fayalite	albite	ortho.	augite	whitl.	sulfide	sulfide	px-glass	lt glass	dk glass
SO ₃	0.02	0.01	0.01	0.02	0.00	0.01	0.00	0.02	96.21	78.01	1.20	0.02	0.03
P ₂ O ₅	0.00	0.00	0.05	0.11	0.07	0.04	0.07	9.41	0.00	0.02	7.22	0.14	0.21
SiO ₂	0.09	0.10	77.81	28.96	66.45	67.84	55.87	34.21	0.01	0.04	34.89	87.27	81.71
TiO ₂	24.72	51.60	0.58	0.15	0.08	0.10	0.72	4.48	1.11	0.00	5.98	0.13	0.14
Al ₂ O ₃	2.00	0.01	15.23	0.04	24.53	23.13	7.25	7.93	0.00	0.01	5.31	7.73	11.48
Cr ₂ O ₃	0.03	0.00	0.01	0.01	0.01	0.00	0.04	0.01	0.00	0.01	0.00	0.01	0.01
MgO	0.09	0.16	0.01	1.76	0.00	0.00	0.82	0.30	0.00	0.00	0.79	0.01	0.06
CaO	0.00	0.00	0.46	0.20	1.03	0.50	11.16	15.20	0.00	0.04	13.30	1.79	2.42
MnO	0.61	0.73	0.01	1.52	0.00	0.00	0.50	0.32	0.01	0.00	0.44	0.01	0.11
FeO	69.76	46.92	1.22	65.54	0.24	0.30	20.79	20.40	80.86	77.82	29.62	1.33	2.22
Na ₂ O	0.01	0.00	1.16	0.00	1.97	1.81	0.62	0.87	0.00	0.00	0.40	0.53	0.42
K ₂ O	0.00	0.00	5.08	0.01	6.53	6.47	1.37	2.79	0.00	0.00	0.17	0.96	1.46
total	97.32	99.54	101.64	98.34	100.93	100.20	99.24	95.94	178.36	156.29	99.31	99.94	100.30
<i>Early-forming phosphate host</i>										<i>Late-forming phosphate hosts</i>			
phase	glass	sulfide	whitl.	glass	fayalite	glass	fayalite	glass	glass?	augite	timag.		
SO ₃		96.21	0.02	0.01	0.02	0.01	0.02	0.01	0.01	0.00	0.38		
P ₂ O ₅		0.00	43.57	0.11	0.03	0.10	0.03	0.10	1.04	1.03	0.00		
SiO ₂	90.60	0.01	0.09	73.98	48.01	75.27	48.01	42.30	41.97	41.97	1.71		
TiO ₂	0.18	1.11	0.02	0.23	0.93	0.19	0.93	2.82	2.74	2.74	25.08		
Al ₂ O ₃	4.63	0.00	0.07	16.50	5.43	16.51	5.43	3.30	3.33	3.33	5.58		
Cr ₂ O ₃	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.01	0.02	0.01		
MgO	0.06	0.00	0.50	0.01	1.03	0.00	1.03	0.89	0.91	0.91	0.04		
CaO	1.08	0.00	46.83	1.42	16.78	1.55	16.78	17.36	17.40	17.40	0.31		
MnO	0.02	0.01	0.21	0.02	0.58	0.03	0.58	0.72	0.76	0.76	0.56		
FeO	0.20	80.86	5.41	0.85	26.49	0.84	26.49	30.79	30.90	30.90	64.49		
Na ₂ O	1.12	0.00	1.22	1.32	0.47	0.69	0.47	0.21	0.21	0.21	0.08		
K ₂ O	2.92	0.00	0.04	5.12	0.76	4.24	0.76	0.01	0.01	0.01	0.14		
Total	100.82	178.36	97.98	99.65	100.55	99.45	100.55	99.48	99.31	99.31	98.39		

subhedral grains and elongated, needle-like grains more than 1 cm long. QUE 94201 also exhibits significant amounts of "dark, mottled lithology" similar to those in Zagami. In summary, although the basaltic shergottites share major mineralogical characteristics, they exhibit differences in the modal abundance and habit of major minerals. In addition, they exhibit textural and modal differences from area to area (in QUE, on the scale of thin sections) within each meteorite, with the exception of Shergotty, whose main mass has not been examined in detail.

The melt inclusions Melt inclusions can occur in any phase that grows skeletally; in the basaltic shergottites these phases include pyroxene, olivine, oxides and phosphates. Given that these minerals crystallize at different stages in the history of the rock, it is not surprising that each kind of inclusion exhibits distinct mineralogical and textural features. Our observations of these features, including previous studies, are as follows.

-Inclusions in pyroxene Trapped melt inclusions in pyroxenes are the only ones to have been previously studied in detail (and only in Zagami and Shergotty), although inclusions in oxides and phosphates had been noted [2,3,5,8]. Typically these inclusions are quite small (a few tens of microns across), surrounded by a network of radial cracks, and contain both glass and daughter crystals (Fig. 1). Many different daughter phases have been identified during our work and previous studies, including spinel, amphibole, Ti-rich augite, titanomagnetite, ilmenite, pyrrhotite, chlorapatite, and whitlockite [2,3]. As might be expected during pyroxene crystallization, the first phase to crystallize from the trapped melt inclusion is additional host pyroxene, resulting in the observed radial fractures as shrinkage occurs. A second pyroxene is common in the inclusions, usually lining part or all of the inclusion wall. This second pyroxene, often a Ti-rich augite, is quite distinct from the enclosing pigeonite in composition but difficult to distinguish optically. Amphibole, when present, also commonly occurs as a wall-lining. Phosphates, spinels, oxides and sulfides usually occur as small needles or equant euhedral crystals, nucleating off the inclusion walls and usually partially embedded in the surrounding pyroxene. Not all inclusions show all the phases seen, most likely because the random cut of thin sections through the rock does not always show all the phases present. Table 1 shows representative mineral compositions for pyroxene melt inclusion phases.

-Inclusions in oxides Trapped melt inclusions in oxides in Zagami and Shergotty have been noted by several authors, but have not been previously studied [2,5,8]. All of the basaltic shergottites contain abundant late Fe-Ti oxides, usually euhedral grains of titanomagnetite containing significant areas of exsolved ilmenite. Textural and fractional crystallization studies of these oxides indicate that they began forming sometime not long after the onset of pyroxene crystallization and increased in abundance throughout the remaining crystallization history of the rock, as the content of Fe and Ti increased in the parental magma. Inclusions in oxides are large by comparison to those found in pyroxene, centrally located within the host grain, and can be in contact with either Fe,Ti-oxide phase, indicating that they were trapped early in the growth of the host crystal. In general, the inclusions are largest and most numerous in basaltic shergottite lithologies with the most evolved composition and coarsest overall grain size- the largest oxide-hosted inclusions are found in Zagami's dark mottled lithology, while the smallest are found in Shergotty and EETA 79001. Again, this probably reflects the increased Ti-Fe content of the magma and may also indicate slow cooling rates at the terminus of crystallization.

Inclusions in oxides are relatively simple by comparison to those found in pyroxene hosts. Their general form is quite rounded, and often a host crystal will contain several inclusions with identical mineralogies. Ti-Fe oxide-hosted inclusions take two general forms. Inclusions trapped in early formed oxides exhibit an exterior mantle of pyroxene surrounding interior glass, indicating that the liquid they trapped was still crystallizing abundant pyroxene (Fig. 2a). This type of inclusion predominates in Shergotty, EETA 79001, and fine-grained lithologies in Zagami. Inclusions trapped in later-formed oxides are predominantly glassy and contain a smaller amount of mafic silicates- they rarely show much pyroxene content, and can contain crystallites of fayalite similar to those found in the mesostasis of Zagami's dark mottled lithology (Fig. 2b). The glass in later-formed inclusions contains many of the same phases seen in pyroxene inclusions, such as needles of chlorapatite, and very small oxide and sulfide grains. In addition, the glass often

Figure 2. Backscattered electron photomicrographs of representative Ti, Fe-oxide grains bearing magmatic inclusions. **a.** shows two typical inclusions within a single early-formed exsolved oxide grain (consisting of titano-magnetite (tm) and ilmenite (il), exhibiting a pyroxene mantle (px) surrounding interior glass (gl). **b.** shows a large inclusion in a late-formed Ti,Fe-oxide grain, containing wall-nucleated and suspended grains of fayalite (fa), chlorapatite (ca) and surrounded by a glass rich in anorthite (an) and orthoclase (or) crystallites (visible as subtle light and dark patches in the grey background). **c.** Oxide-hosted inclusion showing "channel" linking interior inclusion to external mesostasis.

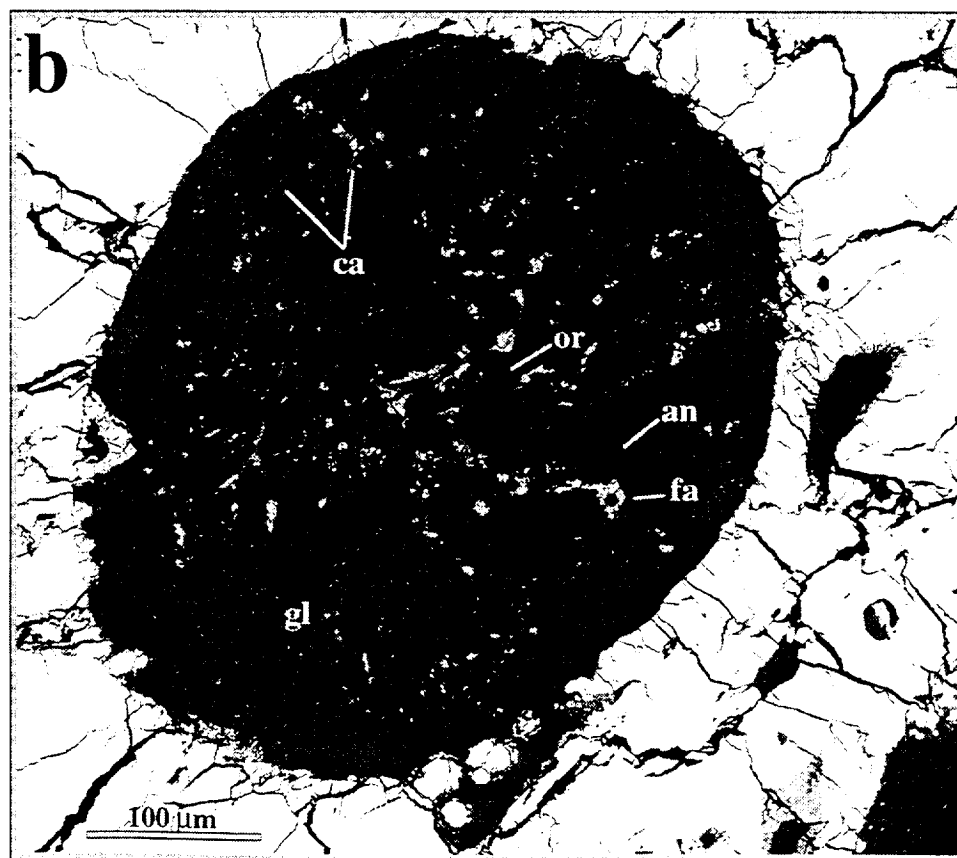
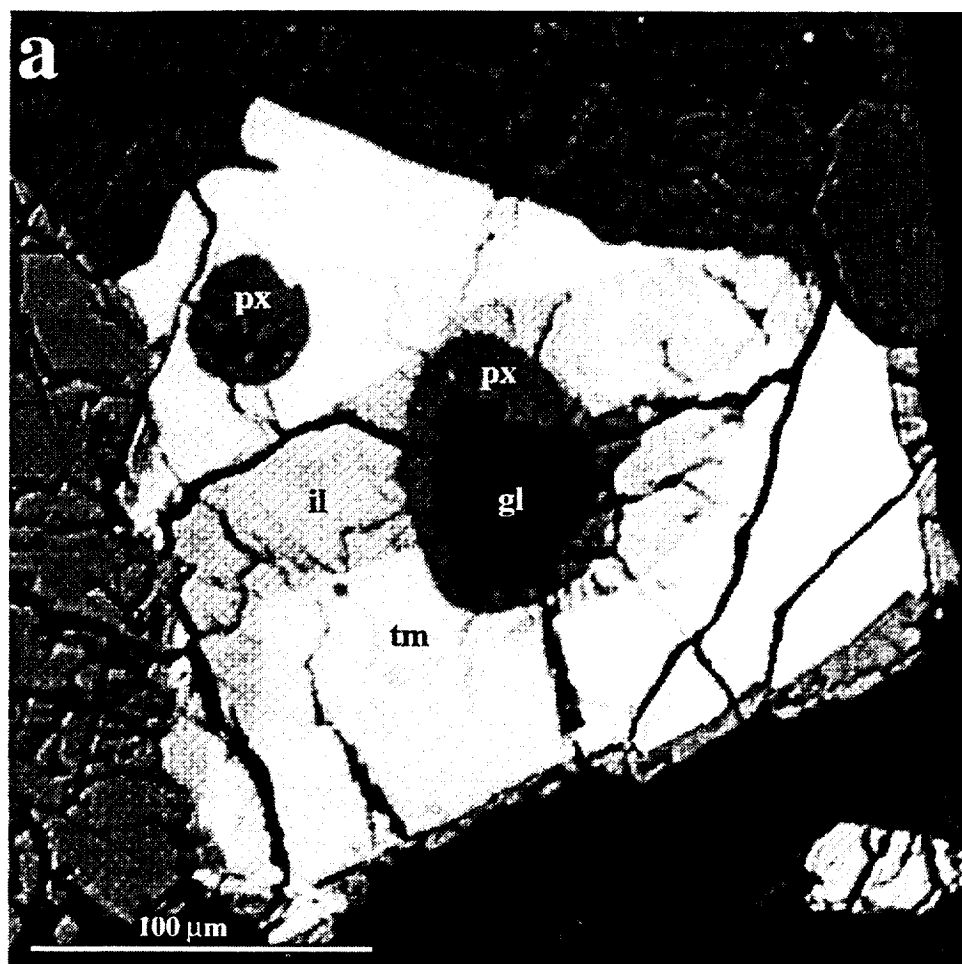




Figure 3. Backscattered electron photomicrograph of representative inclusion in phosphate. The host crystal is composed of whitlockite (wh), and the inclusion consists of fayalite (fa) and sulfide (sf) daughter crystals nucleating off the walls and ends of the inclusion within the interior glass (gl).

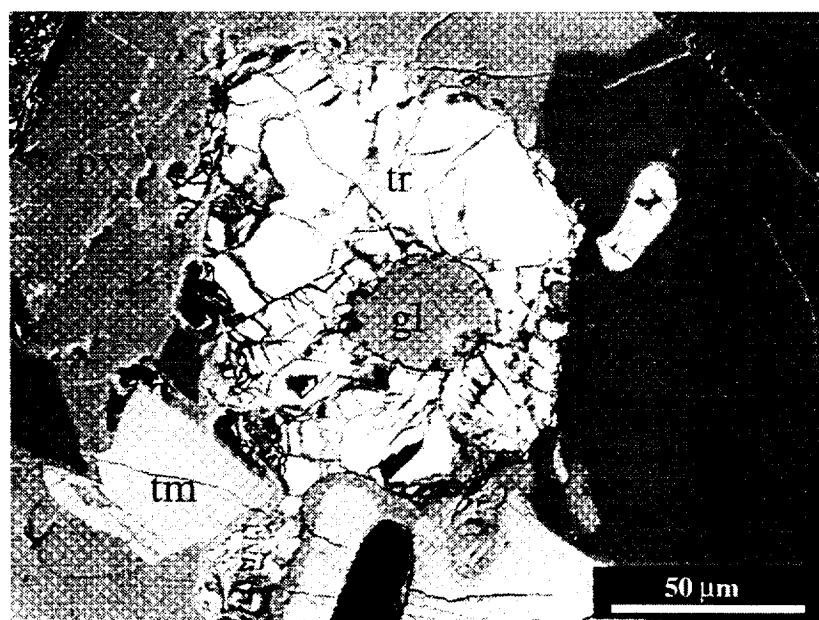


Figure 4. Backscattered electron photomicrograph of representative inclusion in sulfide. The host crystal is composed of troilite (tr), and the inclusion consists of a pyroxene-normative glass (gl). Surrounding phases consist of pyroxene (px), titanomagnetite (tm), and maskelynite (mk).

contains abundant feldspar crystallites, both anorthite and orthoclase compositions. These later-formed inclusions are commonly found in oxides within coarser basaltic shergottite lithologies such as that shown in QUE, and the dark mottled lithology of Zagami. Some inclusions of both types exhibit “channels” that extend from the interior inclusion through the host crystal to the surrounding mesostasis (Fig. 2c). Representative compositions of phases from inclusions within oxides can be found in Table 1.

-Inclusions in phosphates Trapped melt inclusions in phosphates have been noted previously but, as with the Ti,Fe oxides, not actively studied [2,8]. The basaltic shergottites contain two distinct phosphate phases; whitlockite (in early papers misidentified as merrillite) is the most abundant phase, and minor chlorapatite can be found in highly evolved mesostasis areas and within magmatic inclusions. Both phases are predominantly euhedral, forming elongated lathes or needles, and are found as interstitial or mesostasis components indicating they form very late in the crystallization history of the rock. All of the inclusions studied here were in host crystals of whitlockite.

As is the case with oxide-hosted inclusions, phosphate-hosted inclusions are usually central to the parent crystal and tend to follow its original crystallographic structure, taking the form of an elongated, round-ended tube. As is the case for oxide-hosted inclusions, there are some distinctions between inclusions found in less evolved lithologies and those found in more evolved lithologies. Phosphates from Shergotty and fine-grained Zagami lithologies often contain multiple inclusions and are usually nearly pure glass with few daughter crystals. This glass is a uniform, silica-rich composition distinct from the feldspar-normative glass found in pyroxene and oxide inclusions, suggesting that phosphate crystallized after feldspar crystallization had ceased. Phosphates in more evolved lithologies such as QUE 94201 and the dark mottled lithology of Zagami are more likely to contain a single large inclusions than multiple smaller ones, and these larger inclusions often contain abundant daughter crystals of sulfides, fayalite, and Fe-rich pyroxene nucleating off of the walls of the inclusion, in addition to the interior glass.

Representative compositions of phases from inclusions within phosphates can be found in Table 1.

-Inclusions in sulfides Trapped melt inclusions in sulfide have not been identified previously in the basaltic shergottites. Of the four specimens studied here, only EETA 79001 contains this type of inclusion, which is relatively simple in form. The significance of the absence of sulfide inclusions in the other basaltic shergottites is not known. Typically, inclusions in sulfide are of oval shape and occupy the center of the host grain (Fig 4). EETA 79001 has experienced heavy shock and in most cases the sulfide exhibits significant fracturing. Two different inclusion compositions have been noted; a two-phase glass exhibiting possible immiscibility textures, and a single-phase pyroxene normative glass. Representative compositions of phases from inclusions within sulfides can be found in Table 1.

DISCUSSION / DIRECTIONS FOR FUTURE WORK

The basaltic shergottites are all very similar in terms of the minerals present, and like most basalts probably originated as partial melts of more primitive mantle material. However, the four specimens examined in this study show enough variation to make it certain they have experienced, at a minimum, distinct crystallization histories. Because magmatic inclusions have trapped a small portion of the ambient magmatic fluid, and then allowed it to develop as a “captive” small closed system, they serve as excellent tracers of the evolution of a lithology. The glass found within magmatic inclusions is essentially the ambient liquid remaining after the rock has cooled below solidus temperatures. The composition of this glass reflects the parental magma from which the rock formed as well as the host and daughter minerals which crystallized from it. Consequently, careful study of the compositions of the glasses and minerals associated with the inclusions can provide insight into martian magmatic evolution in the following ways.

-Modal mineralogy The type specimen of the basaltic shergottites, Shergotty, is very even in grain size and consistent in terms of abundance of pyroxene, maskelynite, and oxides. EETA 79001, QUE 94201 and Zagami all contain lithologies very similar to Shergotty in these regards, but also contain other distinct lithologies that set them apart. Both EETA 79001 and Zagami show

planar lithological contacts with coarser-grained, more incompatible-rich units, and QUE 94201 shows a wide range of modal abundances and grain sizes over short distances within the small (13g) specimen. Some correlation is seen between the abundance and texture of inclusions and the types of lithologies present in the host specimen. Pyroxene-hosted inclusions are relatively common on Shergotty and fine-grained Zagami, occurring in perhaps one grain in ten, with many grains hosting several inclusions. However, this type of inclusion is rare in the coarse-grained lithology of Zagami, found only in a few, fine-grained regions of QUE, and very rare in EETA 79001. Differences in the growth rate of pyroxene in the various basaltic shergottites is probably the controlling factor, since skeletal growth of the enclosing host phase is required for trapping, and rapid cooling promotes skeletal growth. Given that basaltic shergottite pyroxenes are also strongly zoned, it may prove possible. These variations suggest that it may be possible to correlate zoning profiles of pyroxene with the presence of magmatic inclusions, and establish the relative cooling rates of the various specimens.

-Melt inclusion mineralogy The early inclusions (those in pyroxene and early formed phosphates and oxides) are different from the later inclusions, as is to be expected; between the times that these various inclusions were enclosed, the ambient magmatic fluid was changing composition as it evolved. Examples of these differences include: the presence of Ti-rich augite, spinels, and amphiboles in pyroxene inclusions, when these phases are not seen in the mesostasis; abundant daughter minerals and K feldspars in oxide inclusions in the dark mottled lithology of Zagami, but none in the early inclusions; only Si-normative glass in early phosphate inclusions, while later inclusions contain abundant daughter phases. The evolution of this magmatic fluid in a closed system is due to the crystallization of various primary mineral species, which result in a fluid enriched in elements not used to make minerals, and depleted in elements that are used to form minerals. In addition, the composition of the ambient liquid may change due to open-system behavior; addition of new magmatic fluids, assimilation of local country rock into the magma chamber, or removal of melt or crystals due to eruption or accumulation on the magma chamber floor. Other observations suggest significant open-system behavior of mobile elements relatively early in the crystallization history- the mineralogy observed in pyroxene-hosted inclusions is significantly different than that seen in the rock as a whole, containing spinels, amphiboles, and augites not seen as mesostasis components. In fact, there appears to be a strong correlation between how early an inclusion formed and how distinct it's mineralogy is from that of the rock as a whole, with pyroxene-hosted inclusions being most unlike mesostasis, and late oxide and phosphate inclusions essentially containing an assemblage of minerals identical to mesostasis. Careful study of these changes may help identify the stage in the crystallization history of the rock when the system essentially "closed".

-Parental magmas Determining the composition of the magma that the basaltic shergottites crystallized from is an important goal, because it will allow study of the broader scale geochemistry of the martian crust and mantle. Unfortunately, although the magmatic inclusion represents a trapped parental melt, the subsequent crystallization of host and daughter phases makes it unrepresentative as found in the rock today. However, some careful "reconstruction", adding back together the daughter and host minerals, can allow an estimate of the parent magma's composition to be calculated. Only the earliest trapped inclusions are useful in this regard; the distinctions noted between the crystallization products found in early magmatic inclusions and the mesostasis of these rocks suggest that the magma may have changed significantly before later inclusions were trapped. Using the composition of various inclusion phases as shown in Table 1, initial estimates of the volume of these phases, and some constraints based on known geochemical properties of magma-mineral interactions, linear regression techniques allow a "best-fit" possible parent composition to be produced [9]. At this time calculations have been performed only on magmatic inclusions in Zagami pyroxenes and oxides, as shown in Table 2. So far these calculations have not produced any surprises, generating compositions that are similar to those produced during previous work (Fig. 5). However, continued work should produce compositions for the other specimens, and provide insight into their possible petrogenetic connections. Reconstruction of later-trapped inclusions, although not representing truly parental compositions, will offer

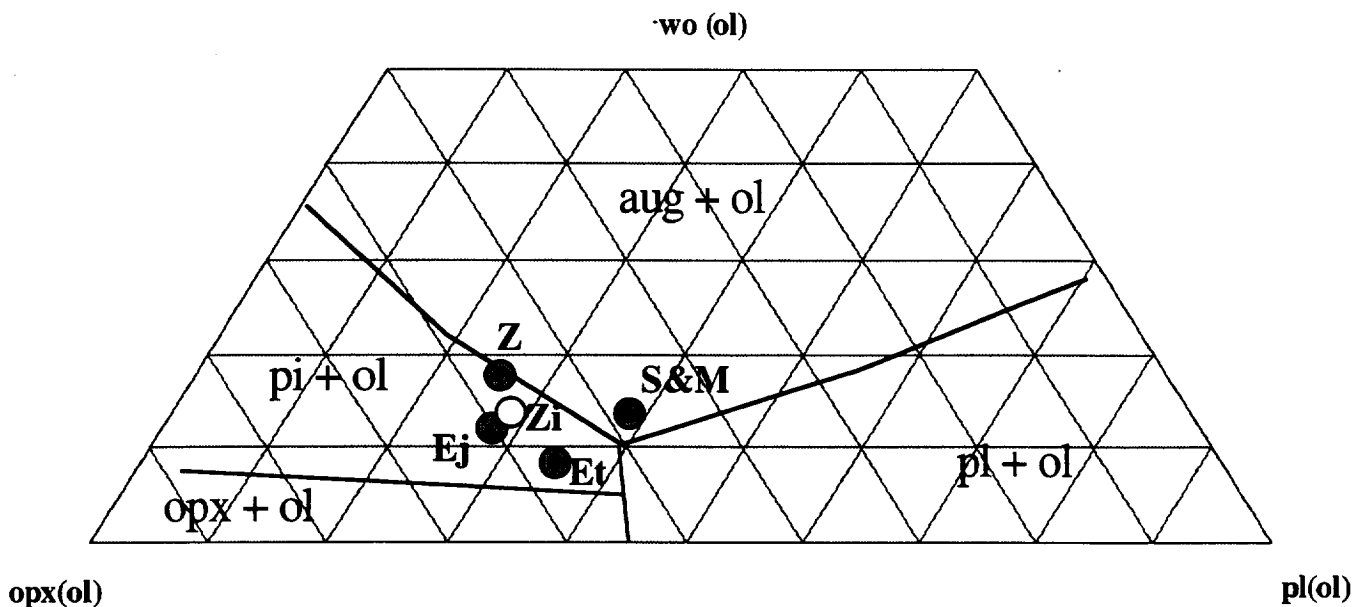


Figure 5. Phase diagram showing the relationship of various proposed parent melts for basaltic shergottites. Dark circles represent proposed parental melt compositions, as projected from olivine in the basalt tetrahedron, are shown as follows. **Z** is the Zagami parent melt from [4], **E** is the EETA79001 parent melt from [6,10], **Et** is EETA79001 from [11], **S** is the Shergotty parent melt from [5]. The white circle labelled **Zi** is the proposed parental melt calculated in this work, based on magmatic inclusions in primary pigeonite in Zagami.

Table 2. Major element composition of possible parent magmas of the basaltic shergottite meteorites. Labels (**Ej**, **El**, **Zi**, etc.) are as shown in Fig. 5.

	Ej (EETA79001) from [6]	El (EETA79001) from [10]	S (Shergotty) from [5]	Et (EETA79001) from [11]	Z (Zagami) from [4]	Zi (Zagami) This work
SiO₂	49.20	50.67	50.10	56.50	51.20	49.27
TiO₂	0.78	0.86	1.08	0.69	0.81	2.52
Al₂O₃	6.44	7.10	9.45	12.00	6.19	6.84
MgO	14.40	12.22	5.11	8.40	10.40	9.75
CaO	7.96	8.74	10.00	10.40	10.70	8.10
FeO	18.49	18.67	19.70	7.70	18.20	21.36
Na₂O	0.97	1.07	1.84	1.90	1.29	1.16
K₂O	0.06	0.07	0.24	0.13	0.13	0.82

significant insight into differences in the geochemical evolution of these specimens as well as the evolution of martian basaltic liquids on the whole.

CONCLUSIONS

This work represents the first comprehensive look at magmatic inclusions in all four of the known basaltic shergottites. Inclusions were identified within four different phases; pyroxenes, oxides, phosphates, and sulfides. The textural context of each of these kinds of inclusions was carefully studied, and the abundance and composition of the various host and daughter phases they contain was analyzed. As has been seen during previous, more limited studies, these inclusions are very useful tracers of the history of these rocks. They provide significant insight into the composition of the parental magmas from which the basaltic shergottites formed, as equivalent small samples of the original magmatic liquid they crystallized from. In addition, they offer useful insight into each of the basaltic shergottite's crystallization history. Systematic differences between the siting and composition of the inclusions in the four specimens have been noted, suggesting that each lithology experienced a distinct crystallization history which included open-system behavior to varying degrees. Within individual specimens, detailed comparisons between early- and late-forming inclusions and the mesostasis should allow us to trace the extent of this open-system behavior, and determine to what extent various igneous processes could account for it, such as volatile loss, magma mixing, assimilation, melting, or accumulation. Understanding the number of sources needed to generate the basaltic shergottites, the geological history and setting of the various samples, and what petrogenetic links these meteorites share will help planetary scientists comprehend the nature of volcanic activity on Mars.

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